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Published in:
Maturitas

DOI:
10.1016/j.maturitas.2016.09.001

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ABSTRACT

Purpose: Describe age-related differences in women's foot shape using a wide range of measurements and ages.

Study design: Cross-sectional, observational study.

Main outcome measurements: Six foot-shape measurements of each foot: foot lengths, ball widths, ball circumferences, low instep circumferences, high instep circumferences, and heel instep circumference.

Results: 168 women from 20 to over 80 years of age, divided into seven age categories, were included. Older women had significantly greater foot-shape measurements, even after adjusting for Body Mass Index. Ball widths increased 3.1-4.0mm per decade, ball circumferences 5.6-7.4mm per decade, high instep circumferences 0.4-4.8mm per decade, and heel instep circumferences 1.8-1.9mm per decade. Ball widths, ball circumferences, and left high instep circumference plateaued in the 70-75 years-of-age category, and decreased in the oldest age category. For low instep circumference, age did not prevail significantly over Body Mass Index. Foot length was not associated with age.

Conclusion: This study described women's progressive foot-shape changes with age. The findings provide a better understanding of foot-shape changes, mainly found in the forefoot. It demonstrates that for a good fit, shoe design for older adults and for younger adults should differ.

INDEX TERMS

Foot, Foot pain, Ageing, Female, Ill-fitting

ABBREVIATIONS

FL, foot length; BW, ball width; BC, ball circumference; LI, low instep circumference; HI, high instep circumference; HIC, heel instep circumference.

1. INTRODUCTION

Foot pain is present in 20-30% of older adults, displaying a higher prevalence in females than in males [1-4], and in 10-14% of young people aged between 12 and 19 years [5, 6]. Some structural conditions are related to foot pain. Such is the case for plantar fasciitis, hallux valgus, toe deformities, metatarsalgia, calluses and corns, bunions, and ingrowing toenails [1, 7, 8]. These structural conditions may result from friction, repetitive stress in forefoot or heel, toe adaptations to shoe shape, pressure spots on toes, and/or changes in plantar pressure distribution due to wearing an ill-fitting shoe [9-12].

Evidence has shown that individuals with foot pain and foot-morphology problems wore inadequate shoes, and that these were mainly women. The main reason demonstrated for this situation was the use of too small and narrow footwear in relation to foot size [9, 12-14]. In the case of women, the use of high heels was an additional source of foot pain, even later in life [2]. Because off-the-shelf shoes may be based on an "average" foot shape for adult people, the possible effects of age on foot shape may not be taken into consideration in the design of shoes. As a result, incorrect shoe designs may be used, which, in turn, lead to a poor fit and consequent foot pain.

A few studies have investigated the potential age-related changes in foot shape. One study analyzed the differences in foot structure and function between young adults and older adults [15]. In so doing, they demonstrated that older feet are flatter than younger feet. This finding was also supported by another study, one based on the assumption that a better understanding of foot morphology would improve shoe fit [16]. Through their anthropometric study of the foot, they showed that foot circumference was markedly larger in the older group. These two studies have shown differences in foot shape between young and older adults, or young adults, adults and older adults; presenting a limited evidence on the progressive evolution of feet. Another study examined changes, as a result of ageing, in the size and shape of the foot [17]. Their findings indicated that older Japanese individuals had wider feet than younger groups. Nevertheless, that study only compares a limited number of measurements among age categories. As a result, an overall description of the genuine process of ageing in feet is lacking.

In response to the limitations found in the literature, the aim of this study was to describe women's foot-shape evolution using a wide range of foot measurements and age categories. In particular, our hypothesis is that a woman's foot shape is continuously changing throughout all stages of adulthood. To test this, several foot-shape measurements were taken from different age categories, with gaps between the age groups in order to highlight the changes among contiguous groups.

2. METHODS

2.1. Study design and setting

This is a cross-sectional, observational study that took place between October 2013 and March 2014 at the University Medical Center Groningen (UMCG), the Netherlands. Participants were recruited through advertising material in supermarkets, public places, homes for older people, and local newspapers. The measurement process was conducted once and lasted 45 minutes. Participants were allowed to rest between measurements, if they needed to. The study is part of a larger project, "The effect of age on foot structure, foot complaints, plantar pressure, and center of pressure in adult women," and has the approval of the Medical Ethical Committee of the UMCG (Number: 2013-225). The project was conducted according to the principles of the Declaration of Helsinki (October 2000) and in accordance with the Medical Research Involving Human Subjects Act (WMO).

2.2. Participants

In the current study, women from the age of 20 until over 80, from the north of the Netherlands, took part. They were divided into categories with gaps of five years between them, so that differences among the groups could be highlighted. Subjects were included if they: (1) were Caucasian women, (2) fitted into one of the age categories, and (3) presented a self-reported ability to walk at least ten meters without any walking aid. Contrarily, participants were excluded if they: (1) reported medical conditions that had a major influence on gait (Parkinson's disease or stroke); (2) had undergone a lower limb amputation; and/or (3) currently used orthopedic footwear (the use of insoles was accepted, however). All participants signed the informed consent form.

2.3. Measurements

2.3.1. Procedure

Before the actual assessment, the participants met with the measurer. In these meetings the eligibility of the participants was determined, the measuring procedures were explained, signed informed consents were collected, and participants were given the opportunity to ask questions. Throughout the whole measuring process, participants were barefoot and instructed to maintain a standing position. First, height and weight were measured using a fixed tape on the wall and an analogue weight scale. Then, trained testers took foot-shape measurements as recommended by the orthopedic shoe technicians in the Orthopedic Instrument Manufacturer (OIM) protocol. According to this protocol, measurements were manually taken using a tape, a sliding caliper, and the Brannock device (The Brannock Device®, Liverpool, NY, USA). The tape in the Brannock Device was replaced with a millimeter scale for this study. Both the sliding caliper and tape measure were placed close to the foot over the points marked for foot-shape measurements; under no circumstances were they ever stretched.

2.3.2. Foot marking and measurement

(Insert Table 1 about here)

Before proceeding to take the measurements, predefined locations were marked with a pen on the skin of the foot. These markers were at the level of 1^{st} metatarsal-phalangeal (MTP-I) and 5^{th} metatarsal-phalangeal (MTP-V) joints, proximal base of the heads of 1^{st} metatarsal (MT-I) and 5^{th} metatarsal (MT-V) bones, navicular bone, base of MT-V bone, front of the subtalar joint (bending point between foot and lower leg), and posterior end point of the calcaneus bone. Once the markers were set, the foot-shape measurements were taken (Table 1). One tester took all the measurements for the same subject, beginning with the right foot and followed by the left.

A graphic description of foot markers and foot-shape measurements is shown in Figure 1.

(Insert Figure 1 about here)

Figure 1. Foot markers and foot-shape measurements.

A, antero-lateral side of the foot; B, plantar side of the foot.

Marks (+), indicate markers placed prior to measurements.

FL, foot length; BW, ball width; BC, ball circumference; LI, low instep circumference; HI, high instep circumference; HIC, heel-instep circumference.

2.4. Power calculation

On the basis of the data from a pilot study with four different age categories, a pooled Standard Deviation (SD) of 1.53, giving an effect size of 0.296, was assumed. With α defined as 0.05, power as 0.8, and using seven age categories, a sample size of 168 participants needed for multiple regression analysis was calculated.

2.5. Statistical analysis

Analyses were performed using SPSS software version 22.0 (IBM Corp., NY, USA). For details on the participant's physical (height, weight, and Body Mass Index [BMI]) and foot-shape characteristics, a descriptive statistical analysis was undertaken. To determine the predictive significance of age on foot-shape differences, a series of simple as well as multiple linear regression models were analyzed. Foot-shape measurements (FL, BW, BC, LI, HI, and HIC) were the outcome variables, and the age of the women was the predictor. In the multiple linear regression analyses, the squared term of age was added as a predictor to ascertain a possible plateau effect. Furthermore, the participant's BMI association with age and foot shape was examined using the Spearman's rho correlation in order to establish a possible confounding effect. All variables were included as continuous variables. The predictors and the confounder were entered stepwise forward into the final multiple linear regression model, and included if $p<0.05$. All statistical analyses were conducted at 5% significance and 95% confidence intervals, and adjusted coefficients of determination were reported.

3. RESULTS

3.1. Description of study sample

In the current study, 168 women participated; full data for all of them was available. Women were divided into seven categories, depending on their age at the time of the measurement, with the same number of participants in each: 20-25, 30-35, 40-45, 50-55, 60-65, 70-75, and >80. Participants height ranged from 145 to 189 cm and weight from 44.2 to 126.7 kg; BMI Mean (SD) was 25.67 (5.20), with almost half of the participants showing overweight (47%, BMI ≥ 25 kg/m^2). A description of foot-shape measurements per age category is displayed in Table 2.

(Insert Table 2 about here)

3.2. Univariate linear regression analyses

The results from the univariate linear regression analyses for foot-shape measurements indicate that older age is related to larger foot-shape measurements. Age was a significant positive predictor for almost all foot-shape measurements in both feet: ball widths, ball circumferences, low instep circumferences, high instep circumferences, and heel instep circumferences (Table 3). Age was also a positive but non-significant predictor for foot length measurements. Age explained from 2.3% to 15.9% of foot-shape variance. In general, being older was a predictor of larger foot-shape measurements.

(Insert Table 3 about here)

3.3. Multivariate linear regression analyses

Age and five foot-shape measurements (BW, BC, LI, HIs, and HIC) showed significant correlations with BMI; therefore, it was included in the final multivariate linear regression models. The results of foot-shape measurement changes are depicted in Table 4. Age remained a statistically significant positive predictor for ball widths, ball circumferences, left high instep circumference, and heel circumferences, even when it was adjusted for BMI. The coefficients of the squared term of age indicated a plateau effect in ball widths, ball circumferences, and left high instep circumference. The models explained between 15% and 32.8% of the measurement's variation. Overall, the regression coefficients showed an increase in the measurements over time in most of the foot-shape measurements, although they plateaued for the majority of the measurements.

(Insert Table 4 about here)

4. DISCUSSION

The purpose of the current study was to describe the ageing process on women's foot shape. The results showed that older women had a significant increase in most foot-shape measurements compared to younger women. This relationship remained after adjusting for BMI. Ball width increased between 3.1 and 4 mm per decade, ball circumference between 5.6 and 7.4 mm per decade, high instep circumferences between 0.4 and 4.8 mm per decade, and heel instep circumferences between 1.8 and 1.9 mm per decade. Nevertheless, ball width, ball circumference, and left high instep circumference plateaued in the 70-75 years age category, and even decreased in the oldest age category. Remarkably, for low instep circumferences, age did not prevail significantly over BMI. Foot length was not associated with age. Women revealed a continuous widening of mainly the forefoot over the years.

In agreement with previous research, the current study has proven that foot shape differs from young adults, to adults, and to older adults [15, 16]. Our study also showed the proportion and location of the changes in foot shape with age. The changes in foot morphology can be explained by the changes in body composition due to the aging process. Muscle strength peaks at 20-30 years of age; from this moment on minor declines occur, and at around 60 years of age a major decline of 1-1.5% per year follows. The underlying reason for this decline in strength is a decrease in the size of muscle mass [18]. In addition, tendons in advancing age change their tensile properties, becoming more compliant [19]. Overall, because of the change in the structure of muscle and tendons with age, foot morphology maintained by these soft tissues is modified, and a wider foot can therefore develop. Moreover, individuals at an older age are more likely to be obese (BMI ≥ 30 kg/m^2) as body weight and BMI peak at 50-59 years of age, and these higher levels of BMI are maintained or decline slightly in the ensuing years [20]. Additionally, overweight and/or obesity have been found to be associated with flatter feet due to the increase in adiposity in the midfoot and altered plantar fat pad [21, 22]. This is consistent with our results, where differences in BMI among participants were significant in all the models, where included. Moreover, BMI showed a major influence in both right and left low-instep circumferences and right high-instep circumference measurements, which could be explained by the increase in adiposity in the midfoot. In addition, flatter wider feet have been also associated with older individuals, when compared to younger adults [15, 17]. Therefore, we suspect that the association of age with BMI could be the underlying reason for these changes.

A singular finding was the significant plateau effect in the 70-75-year age category, and regression in the oldest age category for some of the measurements. Considering that our sample was restricted to women without conditions that have a major influence on gait or who did not use orthopedic footwear, the oldest age category might have been comprised essentially by relatively healthy older women. This, in turn, might explain the decrease in ball width, ball circumference, and left high-instep circumference measurements, given that this age category might have presented higher rates of relatively healthy participants than the other categories.

The difference found between right and left high-instep circumferences is remarkable. The asymmetry within an individual’s feet has been described in literature, and, typically, the left foot tends to be larger than the right foot in right-handers [23]. We believe foot laterality might be a viable additional explanation for high-instep discrepancy; however, since laterality was not measured, this fact could not be demonstrated.

To our knowledge this is the first study describing women's foot shape for a wide range of ages. Major strengths of the study are the equal number of participants per age category, which limits bias toward any of the groups measured. Moreover, the groups were measured in a 5-year age bracket per decade for a more defined difference in foot-shape measurements between groups.

There are some limitations that need to be considered. One limitation would be that various trained measurers were involved; thus, we cannot discard the possibility of differences between them. One other limitation would be the reliability of measurement points. Despite anatomical foot-bone projections for easier localization of the measurement point, it might be difficult to repeat the exact same points. One additional limitation would be the absence of repetition in the measurements. Each measurement was taken only once; therefore, there was no average, and this might bias the outcome. One final limitation would be the selection of the participants involved. Since all the participants were healthy volunteers recruited through advertising material, it might be possible that participants in the older age categories were rather unrepresentative for their age cohort.

We consider it important to emphasize that age, the squared term of age, and BMI, although they are significant predictors for most of the measurements, only explain between 15% and 32.8% of foot-measurement variance. As a result, future research should aim to analyze a wider number of factors associated with foot-shape change. Possible comorbidities as diabetes, structural conditions as hallux valgus, or pregnancy effects, could be some of the factors to take into consideration.

5. CONCLUSION

Growing numbers of older people have foot pain, with the majority of them being women. The need for individuals to be able to independently carry out the activities of daily living is a priority; however, this can be inhibited due to foot pain and ill-fitting shoes. The current study not only shows that the foot shape of women becomes wider with age but also how, since ball width, ball circumference, high instep circumference, and heel instep circumference were found to be larger in older age categories. Furthermore, ball widths, ball circumferences, and left high-instep circumference plateaued at the 70-75-year age category and decreased in the oldest age category. Finally, foot length was not related to age. The findings of the current study demonstrate the continuous change in foot shape with age; therefore, for a good fit, shoe design should be different for older adults as compared to younger ones.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Prof. P.U. Dijkstra for kindly providing statistical assistance; to Mr. J.N. Wijnholds, orthopedic shoe technician, for his recommendations and expertise concerning the measurements; and to the students who collaborated in this study.

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TABLES

Table 1. Description of localization of foot-shape measurements of participants.

Measurement		Location	Device
FL	Foot Length	Distance from the horizontal line situated at the top of the first toe to the back end point of the calcaneal bone in a straight line	Brannock device
BW	Ball Width	Space between MTP-I and MTP-V joints	Sliding caliper
BC	Ball Circumference	Circumference at the level of MTP-I and MTP-V joints	Tape measure around the feet
LI	Low-Instep Circumference	Circumference at a proximal level of the heads of MT-I and MT-V bones	
HI	High-Instep Circumference	Circumference at the level of navicular and base of MT-V bones	
HIC	Heel Instep Circumference	Circumference at the front of the subtalar joint and the posterior end-point of calcaneus bone	

MTP-I, 1st metatarsal-phalanx; MTP-5, 5th metatarsal-phalanx; MT-I, 1st metatarsal; MT-V, 5th metatarsal.

Table 2. Description of foot-shape measurements (mm) of participants per age category; mean ± SD are shown.

		TOTAL (N = 168)	20-25 YEARS (N = 24)	30-35 YEARS (N = 24)	40-45 YEARS (N = 24)	50-55 YEARS (N = 24)	60-65 YEARS (N = 24)	70-75 YEARS (N = 24)	80+ YEARS (N = 24)
FL	**R**	249.0 ± 11.2	244.3 ± 11.8	249.6 ± 9.8	248.4 ± 9.7	249.2 ± 12.5	250.7 ± 9.4	251.2 ± 11.8	249.3 ± 12.8
	L	248.8 ± 11.5	244.0 ± 11.5	249.7 ± 10.7	248.0 ± 9.5	249.2 ± 13.1	250.9 ± 10.4	250.9 ± 11.8	249.0 ± 13.4
BW	**R**	97.4 ± 5.8	94.1 ± 5.6	95.1 ± 4.1	97.8 ± 5.8	98.4 ± 5.2	98.4 ± 3.9	101.3 ± 6.7	96.7 ± 6.5
	L	96.6 ± 5.6	93.4 ± 5.5	95.0 ± 4.4	96.9 ± 4.8	97.3 ± 6.2	97.3 ± 4.6	99.8 ± 5.7	96.7 ± 6.2
BC	**R**	239.9 ± 12.2	233.1 ± 12.1	234.6 ± 8.4	240.1 ± 12.4	241.3 ± 11.9	244.5 ± 8.9	246.6 ± 14.2	239.2 ± 11.7
	L	239.2 ± 11.9	232.9 ± 13.2	235.4 ± 8.8	239.8 ± 10.9	240.8 ± 13.7	241.5 ± 9.3	245.0 ± 12.3	239.3 ± 11.5
LI	**R**	230.5 ± 10.8	227.0 ± 11.3	226.0 ± 8.5	230.7 ± 10.5	230.5 ± 11.6	232.8 ± 8.7	235.1 ± 12.3	231.6 ± 11.0
	L	230.6 ± 10.9	227.4 ± 11.4	227.3 ± 9.7	231.3 ± 10.2	230.9 ± 12.6	231.3 ± 9.5	235.1 ± 10.9	231.1 ± 11.2
HI	**R**	246.4 ± 11.2	241.3 ± 11.0	241.7 ± 12.8	247.8 ± 11.9	247.0 ± 8.6	249.2 ± 9.8	248.5 ± 10.9	249.5 ± 11.2
	L	245.9 ± 12	239.6 ± 11.2	242.3 ± 12.2	248.1 ± 12.0	247.1 ± 9.8	248.1 ± 11.6	249.3 ± 12.7	246.9 ± 12.7
HIC	**R**	319.0 ± 16.1	308.0 ± 14.9	313.3 ± 15.4	318.8 ± 14.6	316.7 ± 10.3	323.9 ± 12.9	325.2 ± 15.8	327.2 ± 19.6
	L	318.7 ± 15.7	307.6 ± 14.3	311.6 ± 13.7	318.3 ± 14.1	317.7 ± 10.0	323.6 ± 12.7	326.2 ± 17.4	326.1 ± 17.9

FL, foot length; BW, ball width; BC, ball circumference; LI, low-instep circumference; HI, high-instep circumference; HIC, heel-instep circumference.

R, right-foot measurements; L, left-foot measurements.

Table 3. Univariate linear regression of age for foot shape characteristics.

		B	SE (B)	95% CI LL	95% CI UL	Sig.	Adjusted R^2
FL	**R**	0.07	0.04	-0.01	0.15	0.094	0.011
	L	0.07	0.04	-0.02	0.16	0.107	0.010
BW	**R**	0.07	0.02	0.03	0.11	0.001	0.054
	L	0.07	0.02	0.03	0.11	0.002	0.052
BC	**R**	0.16	0.05	0.07	0.25	0.001	0.065
	L	0.14	0.04	0.05	0.22	0.002	0.048
LI	**R**	0.12	0.04	0.04	0.20	0.004	0.043
	L	0.09	0.04	0.01	0.17	0.028	0.023
HI	**R**	0.14	0.04	0.06	0.22	0.001	0.056
	L	0.12	0.05	0.04	0.21	0.007	0.038
HIC	**R**	0.30	0.06	0.19	0.41	<0.001	0.139
	L	0.31	0.06	0.21	0.42	<0.001	0.159

FL, foot length; BW, ball width; BC, ball circumference; LI, low-instep circumference; HI, high-instep circumference; HIC, heel-instep circumference.

R, right-foot measurements; L, left-foot measurements.

B, unstandardized regression coefficient; SE (B), standard error for the unstandardized regression coefficient; 95% CI, 95% confidence interval for unstandardized regression coefficient; LL, lower limit; UL, upper limit; Sig., significance.

Table 4. Final multivariate linear regression analyses of age, squared term of age (age^2), and BMI for foot-shape measurements.

			B	SE (B)	95% CI LL	95% CI UL	Sig.	Adjusted R^2
BW	**R**	Constant	78.99	3.23	72.61	85.37	<0.001	0.174
		Age	0.40	0.12	0.16	0.64	0.001	
		Age^2	-0.003	0.001	-0.005	-0.001	0.003	
		BMI	0.31	0.09	0.14	0.48	<0.001	
	L	Constant	80.69	3.17	74.44	86.94	<0.001	0.150
		Age	0.31	0.12	0.08	0.54	0.010	
		Age^2	-0.002	0.001	-0.005	0.000	0.021	
		BMI	0.30	0.08	0.14	0.47	<0.001	
BC	**R**	Constant	197.45	6.48	184.65	210.25	<0.001	0.242
		Age	0.74	0.24	0.26	1.21	0.003	
		Age^2	-0.006	0.002	-0.010	-0.002	0.006	
		BMI	0.91	0.17	0.57	1.24	<0.001	
	L	Constant	203.62	6.57	190.64	216.59	<0.001	0.184
		Age	0.56	0.24	0.08	1.05	0.023	
		Age^2	-0.005	0.002	-0.009	0.000	0.037	
		BMI	0.81	0.17	0.47	1.15	<0.001	

LI	**R**	Constant	202.08	3.68	194.83	209.34	<0.001	
		Age	0.02	0.04	-0.05	0.10	0.559	0.267
		BMI	1.06	0.15	0.77	1.35	<0.001	
	L	Constant	204.01	3.79	196.54	211.49	<0.001	
		Age	-0.003	0.04	-0.08	0.07	0.934	0.235
		BMI	1.04	0.15	0.74	1.34	<0.001	
HI	**R**	Constant	216.71	3.80	209.21	224.21	<0.001	
		Age	0.04	0.04	-0.04	0.12	0.311	0.270
		BMI	1.08	0.15	0.77	1.38	<0.001	
	L	Constant	205.97	6.31	193.50	218.44	<0.001	
		Age	0.48	0.24	0.12	0.94	0.045	0.263
		Age^2	-0.004	0.002	-0.008	0.000	0.050	
		BMI	1.10	0.17	0.78	1.43	<0.001	
HIC	**R**	Constant	274.12	5.29	263.67	284.56	<0.001	
		Age	0.18	0.05	0.07	0.28	0.002	0.312
		BMI	1.39	0.21	0.97	1.81	<0.001	
	L	Constant	274.09	5.11	264.00	284.18	<0.001	
		Age	0.19	0.05	0.09	0.30	<0.001	0.328
		BMI	1.34	0.21	0.94	1.75	<0.001	

BW, ball width; BC, ball circumference; LI, low-instep circumference; HI, high-instep circumference; HIC, heel-instep circumference.

R, right-foot measurements; L, left-foot measurements.

B, unstandardized regression coefficient; SE (B), standard error for the unstandardized regression coefficient; 95% CI, 95% confidence interval for unstandardized regression coefficient; LL, lower limit; UL, upper limit; Sig., significance.